Vortex Lock-In Deep in the Bose Glass

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We use a Bi gaussmeter of micron dimensions to explore the magnetic field dependence of the magnetization relaxation rate and the critical current down to millikelvin temperatures in untwinned single crystals of $YBa_2Cu_3O_{7-\delta}$ with columnar defects. The response separates into three regimes as a function of the ratio of vortex density to columnar defect density B/B_ϕ: enhancements in both critical current and quantum creep in the dilute limit, vanishing magnetization relaxation at the matching density (the proposed "Mott insulator" phase line), and the emergence of temperature-dependent vortex motion for $B \gg B_\phi$.

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Applications of high temperature superconductors are severely restricted by low critical current densities and high vortex creep rates. The deliberate introduction of columnar defects is presently the best way to increase critical current densities and to shift the line separating the reversible (finite resistance) and irreversible (zero resistance) regions of the phase diagram to higher temperatures and magnetic fields [1–3]. Columnar defects serve as strong pinning centers for vortices along the length of the vortex, and are an example of disorder that is correlated across many CuO_2 planes.

As vortices are introduced into a sample with columnar defects, each vortex becomes pinned on one or more columnar defects. Nelson and Vinokur [4] have mapped a tight binding model in which the vortices can hop between randomly distributed columnar defects onto a previously studied model of quantum mechanical bosons in two dimensions [5]. They find a sharp phase transition between a high temperature vortex liquid of delocalized and entangled vortex lines, and a low temperature "Bose-glass" phase of vortex lines localized on the disordered array of columnar defects, as evidenced by recent experiments [6] and simulations [7]. At low temperatures, the model predicts as well a "Mott insulator" line phase, which occurs at an internal field B_ϕ where each column is occupied by one vortex. At this field, an energy gap opens up, inhibiting the motion of vortices out of the defects as well as the addition of vortices to the system. In the Mott insulator phase, the vortex density should remain locked to the density of the columnar defects over a finite range of fields near B_ϕ.

We describe in this Letter the magnetic response down to millikelvin temperatures of untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals with different columnar defect densities. We emphasize the behavior at our lowest temperature, $T = 100$ mK, where the Mott insulator should be most apparent. In this regime, the vortex decay is not thermally activated, but appears to occur by quantum tunneling [8–10]. Here, we report a sizable enhancement in the vortex creep rate in the dilute limit, $B \ll B_\phi$, and a crossover from pinning dominated by columnar defects to pinning by point defects when $B \gg B_\phi$. Most strikingly, we find that the magnetization decay rate drops nearly to zero close to the matching field, $B \sim B_\phi$.

We measured the magnetization and its time decay as a function of magnetic field, $0 \leq H \leq 75$ kG, and temperature, $0.1 \leq T \leq 4.2$ K, using photolithographically patterned Bi Hall probes, described previously [10]. The gaussmeters were calibrated explicitly for both the Hall and the small magnetoresistive response. Columnar defects along $\hat{c}$ were introduced into untwinned as-grown single crystals of $YBa_2Cu_3O_{7-\delta}$ by irradiation with 605 MeV Xe ions at the ATLAS source. The defect densities were determined by measuring the ion flux. The crystals were polygon shaped platelets, at least (150 μm)^2 in area in the a-b plane and less than 20 μm thick, permitting the ions to create columnar defects from face to face. A crystal with no columnar defects (the "0 kG crystal") was used as a reference and two samples with columnar defect densities of $B_\phi = 10$ and 20 kG, respectively, were broken initially from the same original crystal. The crystals were affixed to the gaussmeter using a thin layer of vacuum grease and centered over the (10 μm)^2 active area of the gaussmeter. A carefully chosen, large, symmetric, untwinned single crystal was irradiated separately with 700 MeV Sn ions to $B_\phi = 20$ kG, and the spatial variation of the magnetic relaxation was resolved with a linear Hall probe array.

With strong pinning from the columnar defects, the external field, applied in the c direction parallel to the columnar defects, should create a Bean state [11] characterized by field gradients within the crystal that are related to the critical current [12]. The Hall probe measures the c-axis component of the field, averaged not over the whole sample, but over the active area of the probe, which covers only a small portion of

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the sample. This is the internal field value B which we report. The internal magnetic field measured as a function of applied magnetic field at $T = 100$ K shows a strong dependence on defect density, as can be seen in Fig. 1. The hysteresis loop for the 0 kG crystal is smooth, whereas the hysteresis loops for the crystals with columnar defects have significant structure, which scales with defect density. In the crystals with columnar defects, the internal field changes very slowly as a function of external field for B close to B_ϕ and $|H| < B_\phi$. For $|H| \sim B_\phi$, B changes rapidly, and for $|H| > B_\phi$, B asymptotically approaches an internal field value near that of the externally applied field. We note that the self-field (B at $H = 0$) of the 0 kG crystal is about the same magnitude as that of the 10 kG crystal. Thus, it is not the magnitude of the self-field that determines the shape of the hysteresis loop.

The form of the hysteresis loops for the crystals with columnar defects can be interpreted as a consequence of two different magnitudes of the critical current in the sample: a high critical current region where the vortex density is less than the defect density, and a low critical current region where the vortex density is greater than the defect density. Based on a model of a superconductor with two critical current regions [13], we confirm that features in the hysteresis loops should scale with B_ϕ, independent of gaussmeter position on the sample. We have demonstrated explicitly that the features derive from columnar defect density rather than simple geometry by measuring the hysteresis loops at a number of different positions within the crystals [13]. The widths of the hysteresis loops (and thus the critical currents) are seen to increase with columnar defect density for fields below B_ϕ, consistent with the prediction [4] of stronger pinning for more closely spaced columns.

Magnetization decay was measured as a function of applied field for increasing and decreasing fields and for positive and negative fields. The field ramp rate was 8 G per second or slower, and care was taken to insure that the sample was always in a complete Bean state for the decay measurement. During the field ramp, the vortices flow, allowing access to all regions of vortex density: $B < B_\phi$, $B = B_\phi$, and $B > B_\phi$. After reaching the measurement field, the decays were recorded over a period of 4 h and showed deviations from a logarithmic time dependence only at short times when the decay rates were large. Although nonlogarithmic relaxation has been predicted for the low current regime in the Bose glass, the high current regime is still expected to decay logarithmically in time [4,14]. At the low temperatures where these measurements were made, the currents in the samples are close to the critical currents over the entire measurement window.

The normalized magnetization relaxation rate, $S = (1/M_0)dM/d\ln(t) = (1/|H - B|)dB/d\ln(t)$, varies rapidly and nonmonotonically with magnetic field. We illustrate in Fig. 2 the dependence of S on H for the Sn irradiated 20 kG crystal at $T = 100$ mK for the increasing and decreasing branches of the hysteresis loop. The arrows indicate the direction of the magnetic field sweep. The open circles on the increasing branch indicate the region where $B < 0$; the filled circles indicate the regions where $B > 0$ for increasing field and $B < 0$ for decreasing field. The crystal is rectangular and our largest, with dimensions of 250 μm $\times$ 470 μm. Two Hall probes were placed along the bisecting line of the long side at distances of 95 μm ("edge" gaussmeter, main frame) and of 120 μm ("center" gaussmeter, inset) from the long edge so that they respond only to the flux front entering from the long side. The peak in S occurs for an external field corresponding to $B \sim 0$, and is followed by a sharp dip and a well-defined minimum in the relaxation rate. The peak and dip occur symmetrically for both field directions, and are clearly evident at both positions

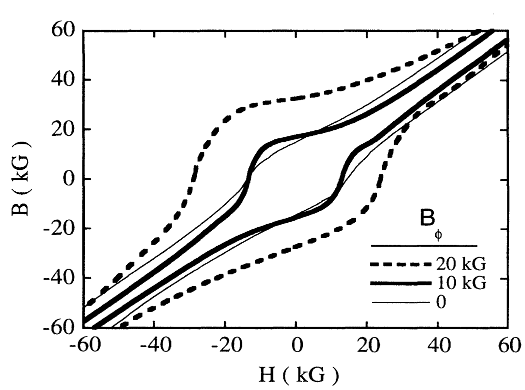

FIG. 1. Hysteresis loops at $T = 0.1$ K for crystals with no columnar defects and with columnar defect densities equivalent to the vortex density at internal magnetic fields $B_\phi = 10$ and 20 kG. The sharp changes in slope scale with B_ϕ.

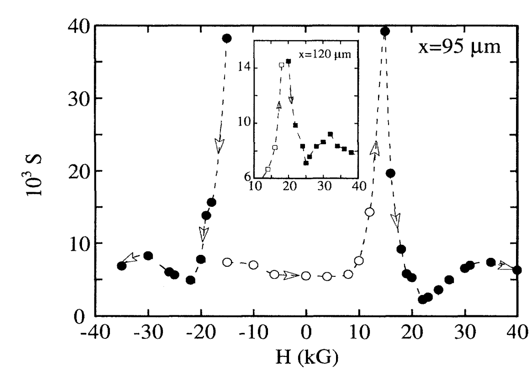

FIG. 2. Normalized magnetization relaxation S vs external field H at two positions distance x from the edge. The maximum in $S(H)$ occurs for $B = 0$, the well-defined minimum occurs at both positions, and S is symmetric about $H = 0$. Arrows indicate direction of the field ramp; open circles correspond to $B < 0$ on the increasing branch.

on the crystal, ruling out any geometrical source [15] for these features. The depth of the minimum, however, is a function of position, indicating a sensitivity to the specific flux configuration. Finally, we note that the external field is not the controlling factor in the decay rate; for a response at the center probe equivalent to that of the edge probe, H must be ramped to a higher value.

Instead of the external field dependence, we examine the decay rate as a function of internal magnetic field. This allows for a direct comparison between the defect density, which is random on small length scales but is constant on average, and the vortex density, which decreases with distance from the edge (on increasing field) because of the combination of the Bean profile and demagnetization effects. We plot in Fig. 3 $S(B)$ at $T = 100$ mK for the 0 kG crystal and the two Xe irradiated crystals for fields where $B > 0$ on the increasing branch of the hysteresis loop. S for $B < 0$ on the increasing branch has qualitatively the same behavior (open circles of Fig. 2). The magnetization decay is substantial (corresponding to the peak in S vs H) when $B < B_\phi$, plummets to a value near zero for fields near B_ϕ, and rises to a secondary maximum before leveling off when vortices far outnumber the columnar defects. The sharp minimum in the magnetization relaxation rate can be interpreted as the opening of an excitation gap [7] (effectively deepening the potential wells and locking the vortices in place) as the vortices fill up the columnar defects at the matching field. It provides strong experimental evidence for the predicted Mott insulator phase line. By comparison, S decreases smoothly with increasing B for the 0 kG crystal, ruling out any instrumental, geometrical, self-field, or "flux annihilation" source for the structure exhibited by the irradiated crystals.

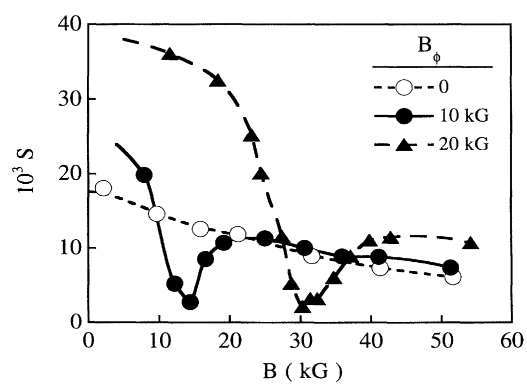

FIG. 3. Scaling of the minimum in the magnetization relaxation rate with columnar defect density at $T = 0.1$ K. The crystal with no columnar defects has no features in $S(B)$, whereas the crystals with $B_\phi = 10$ and 20 kG have large enhancements in S for $B < B_\phi$, a sharp minimum near B_ϕ, and an approach to the point defect pinning limit for $B \gg B_\phi$. Lines are guides to the eye.

The minimum in the magnetization relaxation rate indeed scales with heavy ion dose in otherwise identical crystals, verifying the crucial role of the columnar defects. The pinning near B_ϕ is robust: In the 20 kG crystal, a minimum in $S(B \sim B_\phi)$ still can be discerned at $T = 4.2$ K and at tilt angles between the external field and the c axis of up to 30°. This insensitivity to tilt could reflect another important property of the Mott insulator—the infinite tilt modulus out to a significant angle. The dip in S disappears for $T < 4.2$ K in the 10 kG crystal, indicating a weaker collective pinning energy at lower defect density. The small but finite value of S at its minimum presumably stems from the fact that the field gradient across the crystal prevents the entire sample from being at the matching field at one time. The fact that the minimum in $S(B)$ occurs at approximately $1.5B_\phi$ may result from a combination of the finite size of our probe and the random positional disorder of the defects [16]. It is also possible that S at the position of the gaussmeter may be affected by decay rates in other parts of the crystal.

The enhancement in S at low fields over the 0 kG baseline grows rapidly with columnar defect density. Thus, for $B < B_\phi$, both the magnetization relaxation rate (Fig. 3) and the critical current (Fig. 1) increase with the density of columnar defects. At large internal field, the magnitude of S approaches a value independent of the columnar defects. Here, both the columnar defects and the interstices between columnar defects are occupied by vortices, causing S to cross over to the point defect pinning limit.

In order to gain more understanding of the differences in behavior for $B < B_\phi$ and $B > B_\phi$, we compare in Fig. 4 the temperature dependence of the magnetization relaxation rate in these two regimes for the 10 kG crystal. We find that S is temperature independent up to at least 4.2 K when the columnar defects are not completely filled ($B \sim 8$ kG), while S becomes weakly temperature dependent when the columnar defects are completely filled and vortices must occupy the spaces between defects ($B \sim 27$ kG). The temperature independence of S for $B < B_\phi$ is a strong indication that in the limit where there are fewer vortices than columnar defects vortex motion occurs by tunneling [8–10,17] and that the quantum wells are deep, since thermal activation does not occur even at 4 K. The temperature dependence of S for $B > B_\phi$ is similar to that of other high T_c crystals without columnar defects at equivalent T [9,10]. The temperature dependence revealed at larger fields also provides confidence that the crystals really are cooling down to low temperatures at small B. A crossover between the region dominated by columnar defects and that dominated by point defects occurs at $T \approx 3.5$ K, above which the relaxation of the vortices pinned in the columnar defects is less than the motion of the interstitial vortices.

We have demonstrated that *both* $S(B < B_\phi)$ and $J_c(B < B_\phi)$ increase with increasing columnar defect density. These results are contrary to expectations from

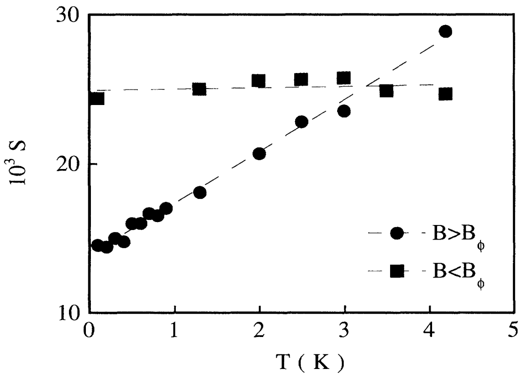

FIG. 4. Temperature dependence of S for the crystal with $B_\phi = 10$ kG, for external fields $H = 15$ kG ($B < B_\phi$) and $H = 30$ kG ($B > B_\phi$). Magnetization relaxation is temperature independent in the dilute limit, indicating the presence of quantum creep, but exhibits a linear temperature dependence in the dense limit.

both the classical theory of strong flux line pinning [18] and present Bose glass models [4] for $B < B_\phi$ and in the limit of slow relaxation, in which $S \propto 1/U_c$ and $J_c \propto U_c$, where U_c is the pinning energy. Experiments at low temperature on single-crystal $Bi_2Sr_2CaCu_2O_8$ with columnar defects do find S decreasing with increasing J_c, but only weakly [8]. However, this experiment is not clearly in either the $B < B_\phi$ or $B > B_\phi$ limit, because the Hall probe was as large as one quarter of the sample area. In other global probes, S also was found to decrease with increasing J_c [2,3], but this dependence was measured down to only 10 K, where thermal effects dominate.

The unusual dependence of S on J_c and the temperature independence of S at low T in our data for $B < B_\phi$ (Figs. 3 and 4) accentuate the need to include quantum processes in describing vortex creep. In the tunneling regime, S may not be determined by the depth of the pinning potential, but by a time scale set by the driving force (J_c) [19]. For $B > B_\phi$, interactions between more densely packed vortices decrease the importance of the columnar defects, and we recover the form observed in unirradiated crystals below 1 K. The evolution simply as a function of B/B_ϕ from enhanced, temperature-independent magnetization relaxation, to virtually no relaxation near $B = B_\phi$, to a temperature-dependent relaxation rate, should illuminate the mechanisms and actual entities contributing to vortex motion.

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Note added.—During revisions, both a theory addressing our results [19] and a related investigation of vortex pinning in a model columnar defect system [20] have been published.

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